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5 Pollux Drive
Edwards AFB CA 93524-7048

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MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO)

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SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-AB-2002-208**
Jimmy Liu (PRSM), "Fracture Mechanics and Service Life Prediction Research" (extended abstract & viewgraphs)

55642

AFOSR Materials & Mechanics Program Meeting
(Arlington, VA, 26-28 September 2002) (Deadline: 20 Sept 02)

(Statement A)

FRACTURE MECHANICS AND SERVICE LIFE PREDICTION RESEARCH

Dr. C. T. Liu
AFRL/PRSM, 10 E. Saturn Blvd.
Edwards AFB CA 93524-7680
Tel. No. 661-275-5642; Fax No. 661-275-5435
E-mail Address chi.liu@edwards.af.mil

Narrative Description of the program:

The goal of this program is to develop a basis for developing advanced crack growth and service life prediction technologies for predicting the service life of solid rocket motors. The objectives of this program are to (1) gain a fundamental understanding of fracture and crack growth behavior in solid rocket motors; (2) investigate the effects of damage, material nonlinearity, pressure, and loading rate on crack growth behavior in a solid propellant; (3) simulate crack growth behavior and gain insight for improving crack growth resistance in solid propellants; and (4) determine the strain rate effect on the constitutive and fracture behavior of bi-material bond systems. The main issues in service life prediction of solid rocket motors are the lack of a fundamental understanding of crack growth behavior under service loading conditions and a reliable methodology to predict crack growth. The main technical challenges are microstructural effects on damage initiation and evolution, large and time dependent deformation, short crack and stress raiser interaction, and multi-layer structures with time-dependent material properties and property gradients. The program's basic approach involves a blend of analytical and experimental studies. In general, mechanisms and mechanics involved in cohesive fracture in a solid propellant and adhesive fracture in bond systems are emphasized. In this program, nonlinear viscoelasticity, fracture mechanics, experimental mechanics, damage mechanics, nondestructive testing and evaluation, and numerical modeling techniques will be used.

These research studies address a number of important subjects such as cumulative damage and crack growth behavior in solid propellants, statistical nature of crack growth, and bonded interface failure. The results of these studies have the potential of becoming some of the most significant contributions to the rocket industry and research community.

Detailed Technical Approach for the Current Fiscal Year:

In FY 02 there are four major tasks: Task 1- investigating the effects of pressure, strain rate, and damage on short crack growth behavior in a solid propellant, Task 2 – developing a failure envelope to predict the critical stress for the onset of growth of short cracks, Task 3 – investigating the three-dimensional effect on crack growth behavior, and Task 4 - determining the strain rate effects on the constitutive behavior as well as on the local damage and deformation in bi-material, propellant/liner/propellant, bond systems.

Task 1: Investigating the Effects of Pressure, Strain Rate, and Damage on Crack growth Behavior in a Solid Propellant

In Task 1, in order to investigate the damage state in a solid propellant under multi-axial loading conditions, a series of tests were conducted on uniaxial specimens without cracks. Prior to conducting the test, the specimen was put in a loading fixture situated inside a pressure chamber. When the pressure inside the pressure chamber reached 1000 psi, the specimen was strained at a strain rate of 0.072 in/in/min. When the applied strain reached 10%, the specimen was unloaded to zero load, and then, it was reloaded with and without 1000 psi confining pressure until fracture occurred. Typical plots of the stress-strain curves are shown in Figs. 1 and 2. From Fig. 1, it is seen that the slope of the reloading stress-strain curve is smaller than that of the initial stress-strain curve. In other words, the Young's modulus of the material is decreased after the specimen was subjected to a 10% pre-strain, indicating damage developed in the material when the specimen was strained to 10% under 1000 psi confining pressure. A comparison between Fig. 1 and Fig. 2 reveals that the slopes of the reloading stress-strain curves are close to each other, indicating that the magnitude of the confining pressure has no significant effect on the Young's modulus of the material when the specimen was damaged by the 10% pre-strain under 1000 psi confining pressure. However, the reloading curves show that the maximum stresses under different confining pressures are significantly different. This phenomenon is believed to be related to the different damage initiation and evolution processes that occur during reloading under the ambient and the 1000 psi confining pressures conditions. At 1000 psi confining pressure, the damage initiation and evolution processes are suppressed, resulting in a slow crack growth, which leads to an increase in material strength.

It is known that the damage state is closely related to the stress state in the material. In order to obtain a fundamental understanding of the damage initiation and evolution processes, the stress states near the filler particles were determined by using a three-dimensional numerical modeling technique. In the analysis, a unit-cell approach was used. In one case, the unit-cell contained two particles, whereas, in the other case, the unit-cell contained four particles. The results of the numerical analysis reveal that, under ambient and 1000 psi confining pressures, high triaxial tensile stress states were developed, near the particle surfaces, between the particles. However, the stress states surrounding the triaxial tensile stress location are different for the two different confining pressure conditions. For the ambient confining pressure condition, tensile stresses fields surround the high triaxial tension location. However, for the 1000 psi confining pressure condition, compressive stresses fields surround the high triaxial tension location. The different stress states under the different confining pressure conditions is responsible for the different damage initiation and evolution processes in the material.

Task 2: Crack Instability and Growth Models

Sub-Task 1: Instability Criteria for Short Crack Growth

In this task, the instability criteria for the onset of growth of short cracks are developed. Based on last year's study, we found that for short cracks, defined as having a crack length equal to or less than 0.1 in., classic fracture mechanics cannot be used to determine the critical condition for the onset of crack growth. In FY 01, a linear fracture mechanics solution was modified to predict the behavior of short cracks. An effective crack length was introduced into the Mode I stress intensity factor. By using the effective crack length, a reasonably good agreement exists between the fracture toughnesses for the onset of growth of short and long cracks. In FY 02, a failure envelope, based on

theories of strength of material and fracture mechanics, was developed. The developed failure envelope can be used to predict the critical stress for the onset of crack growth for short and long cracks under different strain rate and confining pressure conditions.

Sub-Task2: Determining the Damage Characteristics near the Crack Tip

In FY 02, Lockheed-Martin Research Laboratory's High-Resolution Digital Real-Time Radiographic System was used to determine the damage characteristics near the crack tip for different materials. The experimental results reveal that the critical damage intensity for the onset of crack growth is insensitive to loading history and material property. The averaged critical damage intensity for the onset of crack growth for different materials under different loading history is 1724 with a standard deviation of 28.

Sub-Task 3: Investigating the Effect of Confining Pressure on the Critical Initial Crack Length in the Material

In FY 00, a technique was developed, based on fracture mechanics and probabilistic mechanics, to predict the critical initial crack size, which is responsible for the fracture of the specimen. In FY 01, the developed technique was modified to include rate effect. The modified technique can be used to predict the initial critical crack size at different strain rates with good accuracy. In FY 02, the effect of multi-axial loading on the critical initial crack size was investigated. The results of the analysis reveal that the magnitudes of the confining pressure, ambient and 1000 psi, have no significant effect on the predicted critical initial crack length. A comparison between the previous and the present studies indicates that the critical initial crack length and the statistical distribution function are insensitive to specimen's thickness, strain rate, and loading axiality. Therefore, for the material investigated, the critical initial crack length can be considered a material property. The determination of the critical initial crack size and its statistical distribution function will make statistical and reliability analyses of crack growth feasible.

Task 3: Photoelastic Analysis of Three-Dimensional Effects of Cracking of Motor Grain Geometries under Internal Pressure loads.

Prior to October 2001, a series of frozen stress experiments involving a combination of internal pressure and a small axial load were conducted on one tenth scale photoelastic models of a six finned motor grain, each model containing two cracks in separate fins separated by an uncracked fin. (Fig. 3) In these prior tests, it was determined that i) The maximum stress in the uncracked models occurred at the confluence of the two tip radii R1.3 and R11 (Fig. 3) This confirmed analytical data. ii) When cracks of equal depth were placed at the above location and also on the axis of symmetry of a fin, the latter crack always began to grow sooner and further than the former crack which inevitably contained shear modes until it turned as a Class 2 crack. The symmetric crack was always a Class 1 crack.

Figure 4 shows two off axis, inclined cracks initiated at the point of confluence noted above and normal to the fin surface. In Fig. 4, Model 4 shows the early stages of growth where the crack is still turning and exhibits both Modes I and II all around the crack front except at the fin surface where pure mode I exists (as a class 2 crack). In Fig. 4, Model 8-i shows another crack grown from the same location but much further until only Mode I exists along the crack front. Its turning has

been completed as shown by the path of the midpoint of the crack. It has just become a Class 1 crack. The Model 4 crack was 8.71 mm deep and 22.3 mm wide after growth compared to 12.5 mm and 42.2 mm for Model 8-i. River markings on Model 8-i show the presence of Mode III as well as Modes I and II during the Class 2 phase of growth. Clearly this crack is not planar.

Due to the above findings, and the inherent difficulty in repeating Class 2 growth paths, it was decided to introduce the off-axis starter cracks at the point of confluence of the fin tip radii directed parallel to the fin axis. Four new models, each containing 2 cracks of the above type and located as in Fig. 3 were prepared in this manner and tested by the frozen stress method. Test results reveal that the starter crack quickly grow as a Class I crack with virtually no turning, and a decrease in the normalized Mode I SIF with increasing crack depth with a 6% maximum scatter which is the accuracy of the SIF calculations.

Taken collectively, the above studies suggest the following observations: i) Symmetric cracks are more dangerous than off-axis cracks even though they do not start at the locus of maximum stress in the uncracked model. ii) Off-axis cracks directed parallel to the fin axis are also dangerous but less so than the symmetric cracks for they will grow on slightly curved paths and their F_i values decrease with increasing depth. iii) While some of the cracks penetrated the outer wall in the depth direction, none of the cracks penetrated the length of the cylinder.

These results suggest that the practice of using a through-the-cylinder length crack in design maybe a substantial over design and suggests a comparison with deep semi-elliptic cracks as an alternative approach.

Task 4: Deformation and Failure Mechanism of Propellant/Liner/Propellant Bonded Specimens

In FY 01, a series of experiments on propellant/liner/propellant bonded specimens were conducted at 0.01 in/min displacement rate. A computer aided speckle interferometry technique was used to determine the displacement and strain distributions in the specimen. Two interface debonding modes, debonding from the center and the corner of the interface of the specimen, were observed. These debonding modes appeared to be related to the specimen geometry. In addition, the strain rate in the interphase and liner layers increase with increasing time and are significantly different from the constant applied strain rate. In FY 02, a series of tests on propellant/liner/propellant bonded specimens were conducted. At the time of this writing, we are analyzing the test data to determine the effect of the applied strain rate on the deformation and strain distributions in the bonded specimen.
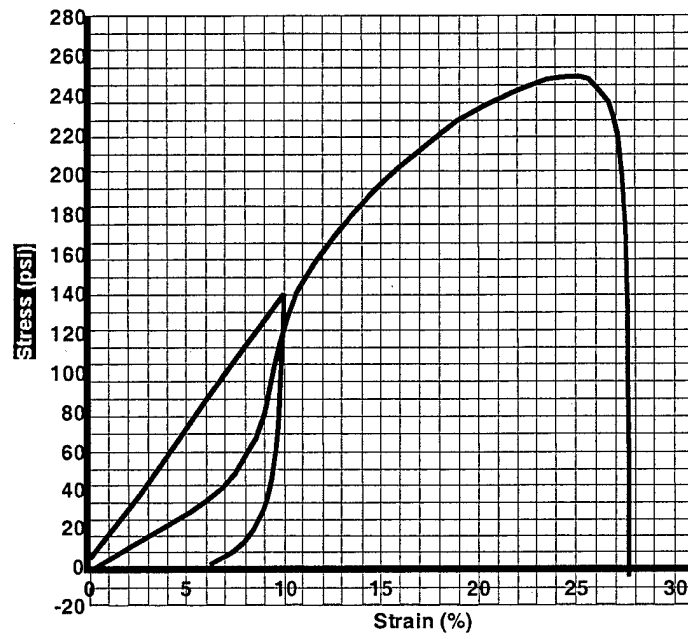
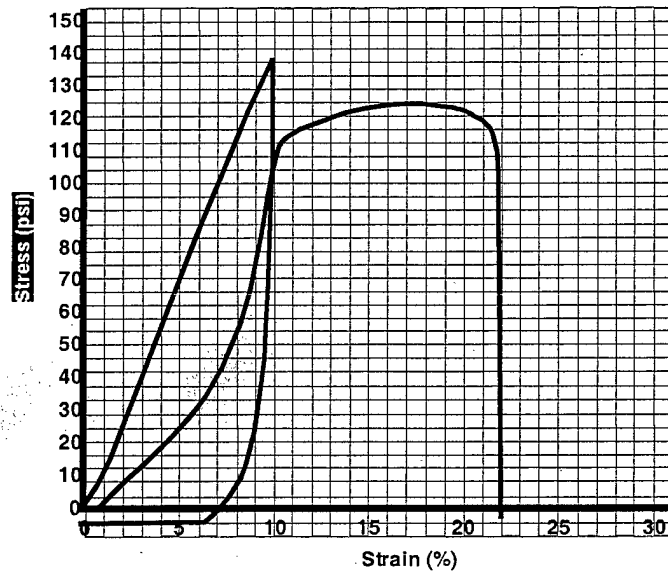Fig.1 Stress-Strain curves (reloading under 1000 psi confining pressure).

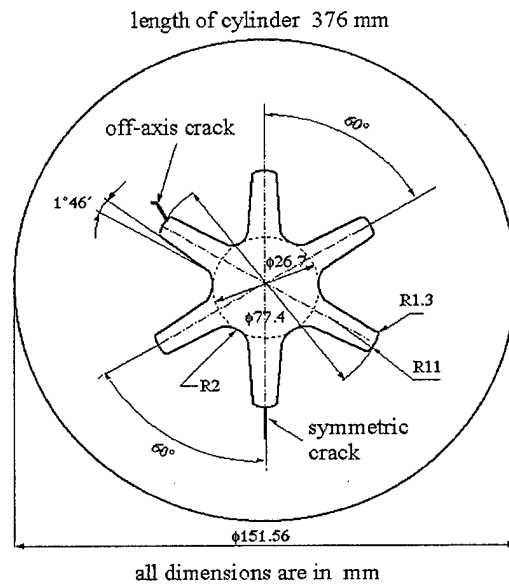Fig. 2 Stress-Strain curves (reloading under ambient pressure)

length of cylinder 376 mm
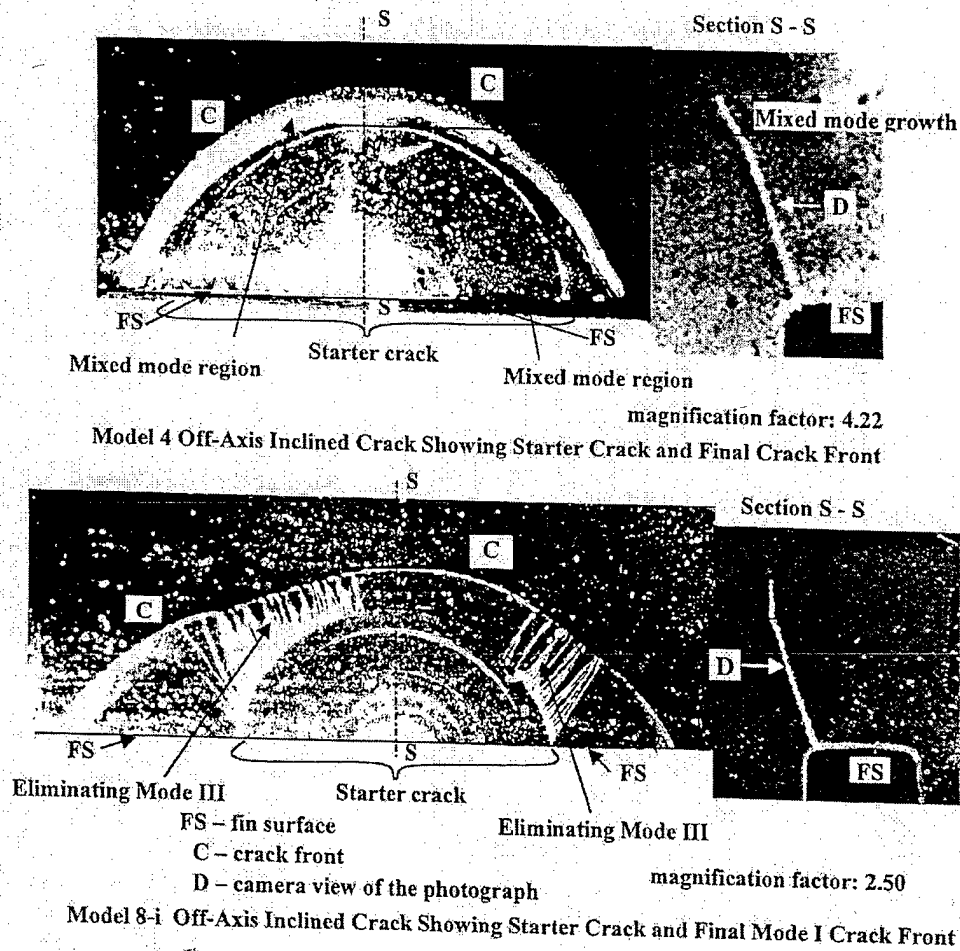

off-axis crack

1°46'

60°

φ26.7

φ77.4

R1.3

R11

R2

60°

symmetric crack

φ151.56

all dimensions are in mm

Fig. 3 Photoelastic model.

S

Section S - S

C

C

Mixed mode growth

C

D

FS

FS

FS

Mixed mode region

Starter crack

Mixed mode region

magnification factor: 4.22

Model 4 Off-Axis Inclined Crack Showing Starter Crack and Final Crack Front

S

Section S - S

C

C

C

D

FS

FS

FS

Eliminating Mode III

Starter crack

Eliminating Mode III

FS – fin surface
C – crack front
D – camera view of the photograph

magnification factor: 2.50

Model 8-i Off-Axis Inclined Crack Showing Starter Crack and Final Mode I Crack Front

Fig. 4 Crack growth profiles

FRACTURE MECHANICS AND SERVICE LIFE PREDICTION RESEARCH

September 2002
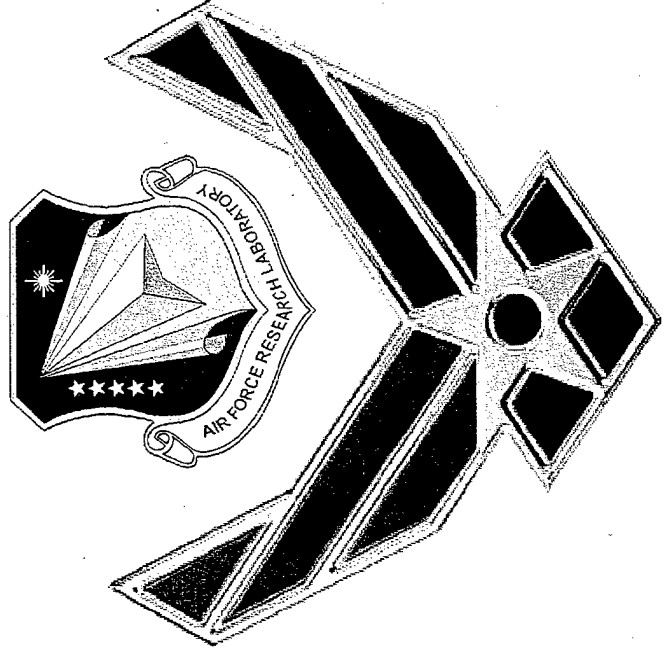
C.T. Liu

Principal Research Engineer

PRSM

Air Force Research Laboratory

Fracture Mechanics and Service Life Prediction Research

★ Objectives:

— Gain an Improvement in Understanding of Damage Mechanisms and Fracture Behavior in Solid Propellants and Insulator/liner/ Propellant Bond System.

— Develop Methods to Predict Crack Growth.

★ State of the Art:

— Deterministic Approach; Material Is Homogeneous; Crack Initiation Failure Criterion

★ Approaches:

— Experiments (Destructive and Nondestructive Tests);

— Analytical Analysis and Numerical Modeling

★ Applications:

— Missile Systems(Titan IV; Minuteman; Air Launch Systems)

Fracture Mechanics and Service Life Prediction Research

* **Past Years Accomplishments:**

  — Developed Rate-Dependent and Temperature-Dependent Probabilistic Crack Growth Models

  — Developed a Nonlinear Viscoelastic Constitutive Model and Incorporated It in a Finite Element Computer Code

  — Developed a Technique to Predict the Inherent Critical Initial Crack Size Under Different Loading Conditions

  — Determined the Effects of Microstructure on Damage Mechanisms and Strain Fields Near the Crack Tip

  — Developed a Technique to Determine the Effects of Residual Stress and Material Mismatch on Stress Intensity Factors at the Tip of Interfacial Cracks in Bi-material Specimens

  — Determined the Applicability of Using Homogeneous Continuum Approach to Analyze Solid Rocket Motors

* **Research Pay Off:**

  — Provide a Fundamental Understanding of Damage Mechanisms and Fracture Behavior in Solid Propellants and Insulator/liner/ Propellant Bond Systems

  — Provide Guidance for Developing High Strength Solid Propellants and Insulator/liner/ Propellant Bond Systems

  — Make Defect-tolerance Analysis Methodology Feasible.

* **Related Research Program:**

  — Fracture Mechanics Support (P.I. Dr. C. T. Liu; AFRL/PRSM)

  — Minuteman Support (P. I. Dr. C. T. Liu; AFRL/PRSM)

  — Service Life Prediction Technology (Program Manager Dr. G. Ruderman; AFRL/PRRM)

  — Critical Defect Assessment Program (Program Manager Dr. G. Ruderman; AFRL/PRRM.

Fracture Mechanics and Service
Life Prediction Research

- **Uniqueness of Research:**

  – Unique Material (Dual Function Material) and Composite Structure.

  – Account for Microstructural Effect on Crack Growth Prediction.

  – Account for Local Behavior in Crack Growth Simulation.

  – Account for Time-Dependent Material Property and Property Gradient in Multi-Layered Structure.

  – Systematic Approach: Micro and Macro Measurement and Analyses.
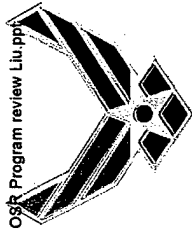
Fracture Mechanics and Service Life Prediction Research

✷Success Story:✷

—Acceptance criteria have been developed and successfully used to determine the criticality of defects in Titan IV solid rocket motors. The total estimated savings to the Air Force are $100M.

Fracture Mechanics and Service Life Prediction Research

⊀Application:

—The advanced service life prediction technology has been successively used to determine the service life of TITAN IV solid propellant grains and will be used to predict the service life of other missile systems.

Fracture Mechanics and Service Life Prediction Research

✕ Significant Accomplishments:

— Developed a Time Independent Constitutive Model, Including Pressure Effect.

— Determined Three-Dimensional Effect on Crack Growth Behavior.

— Determined Load History and Material Property Effects on Critical Damage Characteristics at the Crack Tip for the Onset of Crack Growth.

— Determined Strain Rate Effects on the Material Responses of Bi-material Bonded Specimens.

— Developed a Time-Dependent Constitutive Model, Including Pressure Effect.

— Developed a Technique to Predict the Critical Initial Crack Size in a Solid Propellant.

— Developed a Failure Envelope Criterion to Predict the Critical Stress for the Onset of Growth of Short Cracks Under Different Strain Rate and Confining Pressure Conditions.

The Critical Condition at the Crack Tip for the Onset of Crack Growth is Insensitive to Loading History and Material Property.

Specimen12
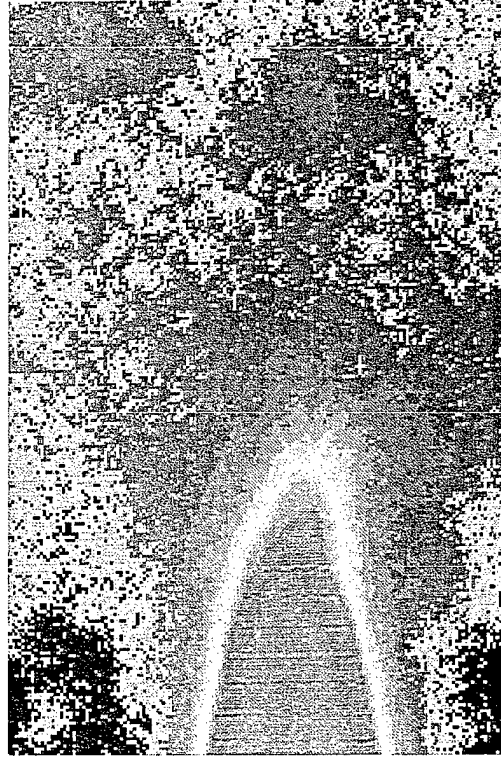
Specimen10

⋇ For the material investigated, the average critical damage intensity Ic, measured by real-time x-ray techniques, for the onset of crack growth for different materials under different loading histories is 1724 and the standard deviation is 28.

⋇ For the loading condition considered, Ic is a material property.

The Critical J-Integral Value for the Onset of Crack Growth is Insensitive to the Loading History

- The critical J-integral values for the virgin and the pre-strained specimens are 2.76 lb/in. and 2.98 lb/in., respectively.

- Pre-strain has a significant effect on the constitutive behavior of the material.
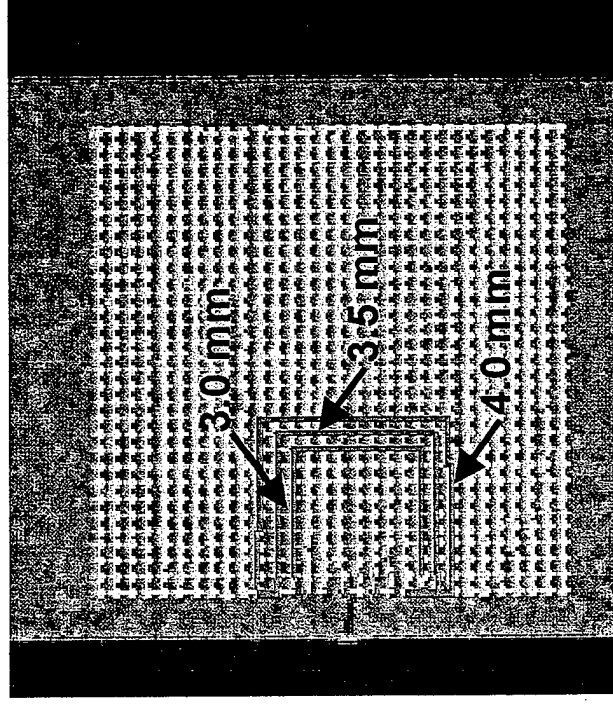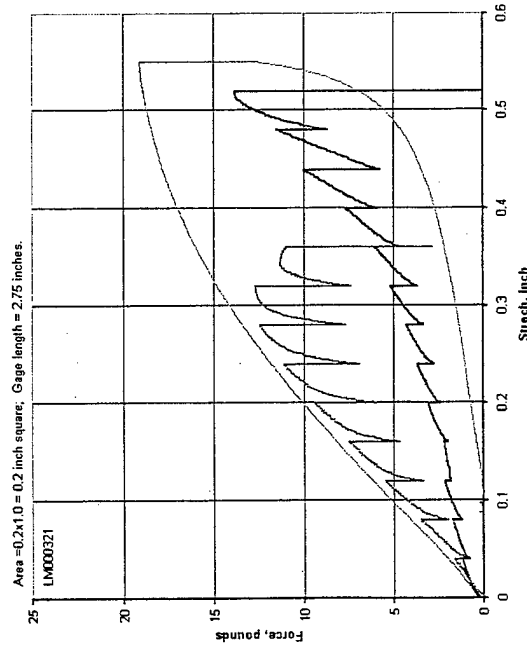
Under A High Confining Pressure, Microcracks Can Develop in the Highly Filled Particulate Composite Material

木 **The development of micro-cracks under multi-axial loading conditions results in a decrease in modulus.**

木 **For a given number of defects (micro-cracks or micro-voids), the modulus (volume dilatation) is insensitive (sensitive) to the type of defects.**
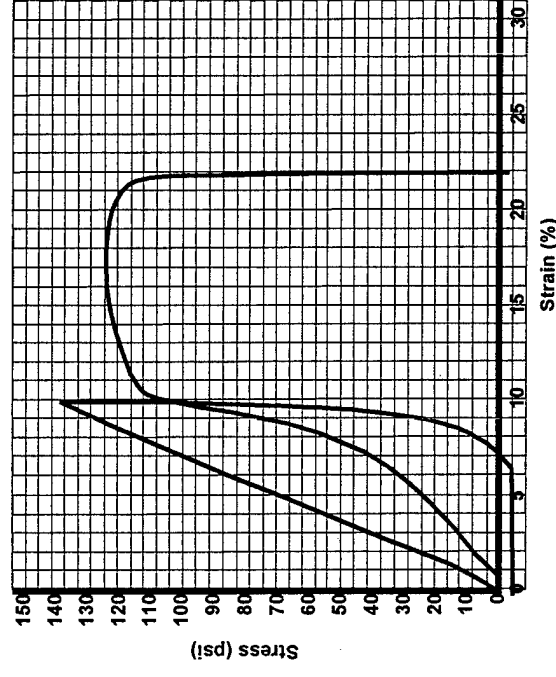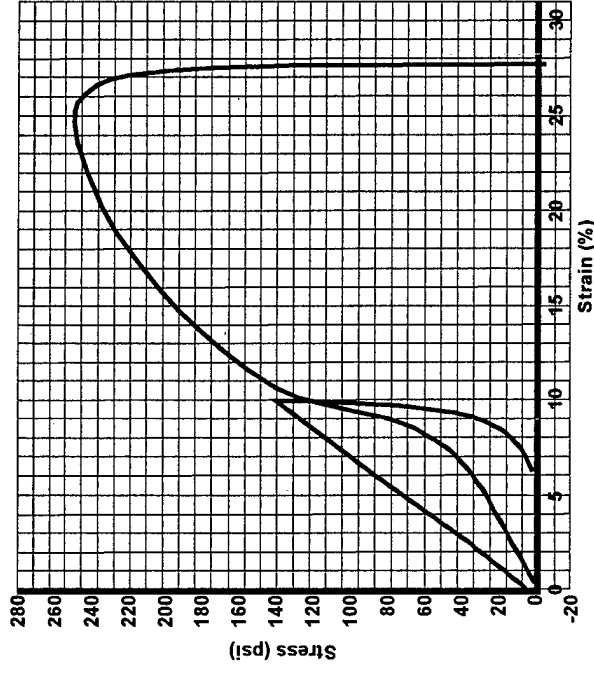
OSR Program review Liu.ppt

Under A Constant Strain Rate Loading Condition, the Failure Mode Changes when the Confining Pressure Changes from Ambient to 1000 psi

Pressure = 72.7 psi

Pressure = 1744 psi

木 Under ambient pressure, voids are formed around the filler particles, resulting in a rough fracture surface.

木 Under 1000 psi pressure, microcracks are formed near the filler particles surface, resulting in a relatively smooth fracture surface.

A Three-Dimensional Numerical Simulation of Particles Interaction Under Multi-Axial Loading Condition Reveals that A High Triaxial Stress State Developed Near The Particle Surface

✳ The high constraint developed near the particle surface induces a high triaxial tension stress state near the particle surface.

confined pressure = 1000 psi

σ_{11} σ_{22} σ_{33}
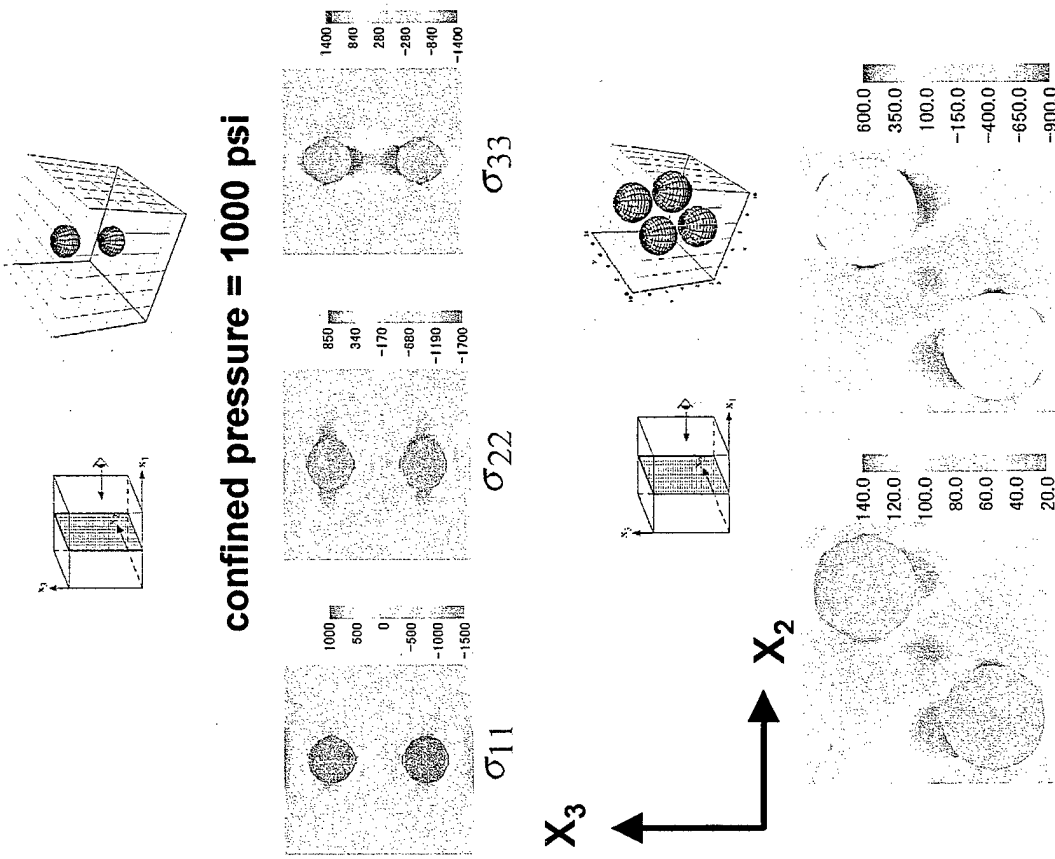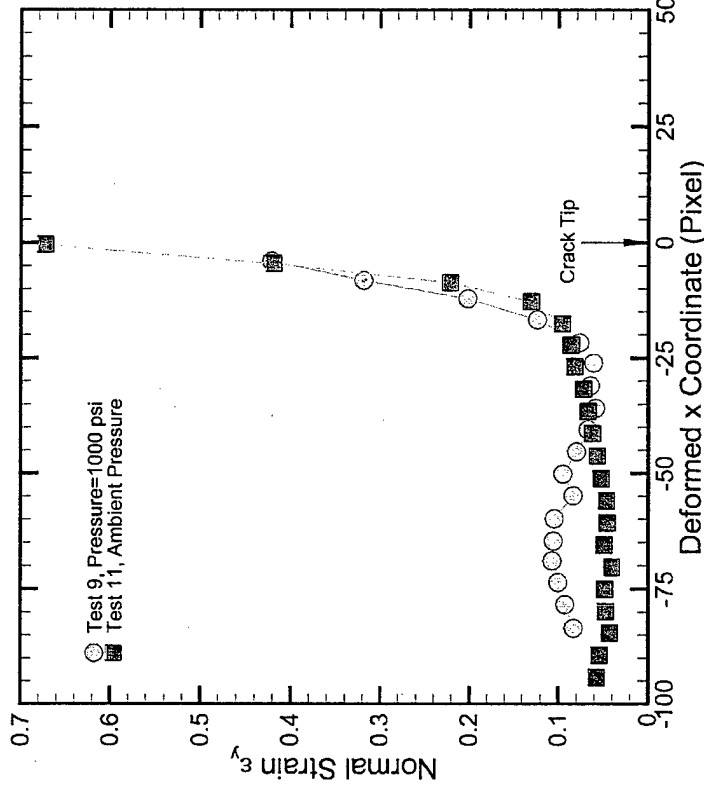
confined pressure = ambient

confined pressure = 1000 psi
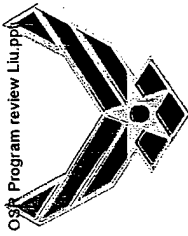
The Loading Axiality has no Significant Effect on the Critical Damage Intensity for the Onset of Crack Growth

Damage Plot at the Same Applied Strain Level (50 in/min)

Damage Plot at the Onset of Crack Growth

- Based on a micro-damage analysis, the damage intensity inside the highly damage zone is insensitive to the loading axiality.

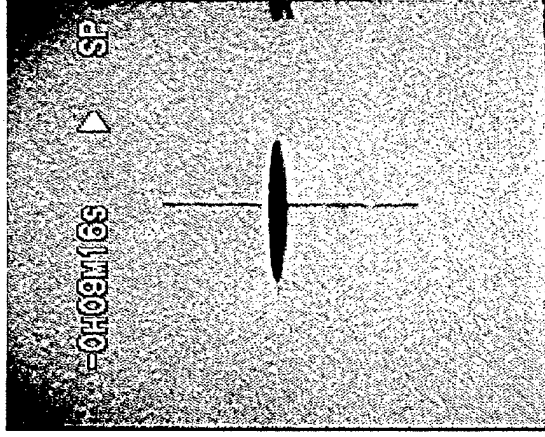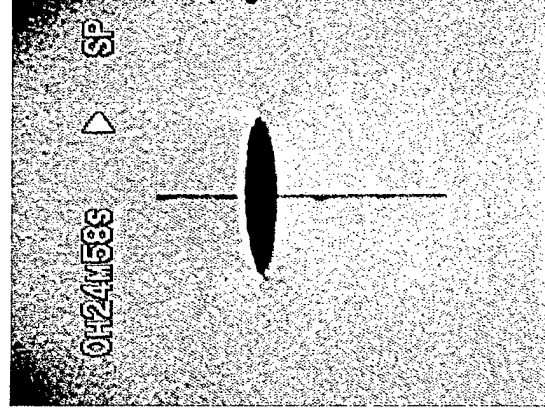- For a given applied strain, the damage intensity is highly dependent on the loading axiality.
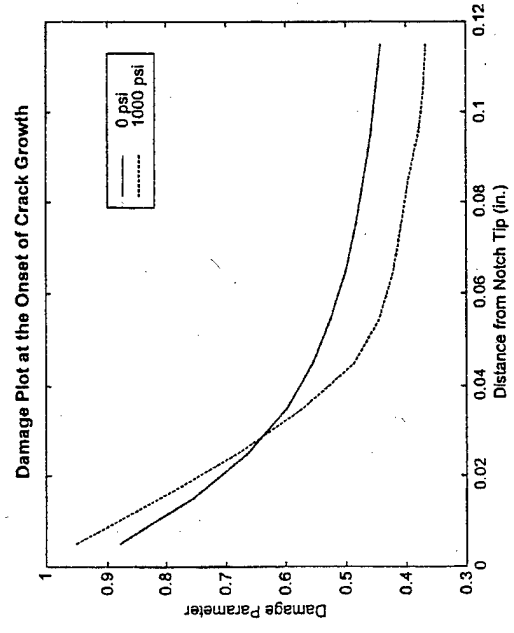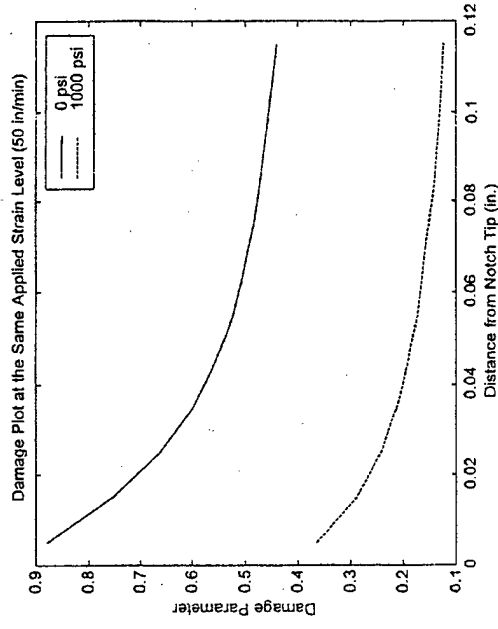
The Loading Axiality has no Significant Effect on the Size of the High Strain Region at the Onset of Crack Growth

1000 psi confining pressure

ambient pressure

Time for test 9: 18/13.75=1.31 s (1.27s is the time when the crack starts to propagate.)

Time for test 11: 10/13.75=0.73 s (0.73s is the time when the crack starts to propagate.)

* At the onset of crack growth the size of the high strain region is 0.63 MM

* The different confining pressures induce different strain distributions ahead of the crack tip

Test 9, Pressure=1000 psi
Test 11, Ambient Pressure

Normal Strain ε_y

Deformed x Coordinate (Pixel)

Crack Tip

18

# Microstructure has a Significant Effect on the Strain Distribution on the Meso-Level.

✗ Experimental findings reveal that a highly irregular strain distribution occurs on the meso-level.

✗ For the solid propellant investigated, there is no theoretical solution that matches the measured strain distribution on the meso-level
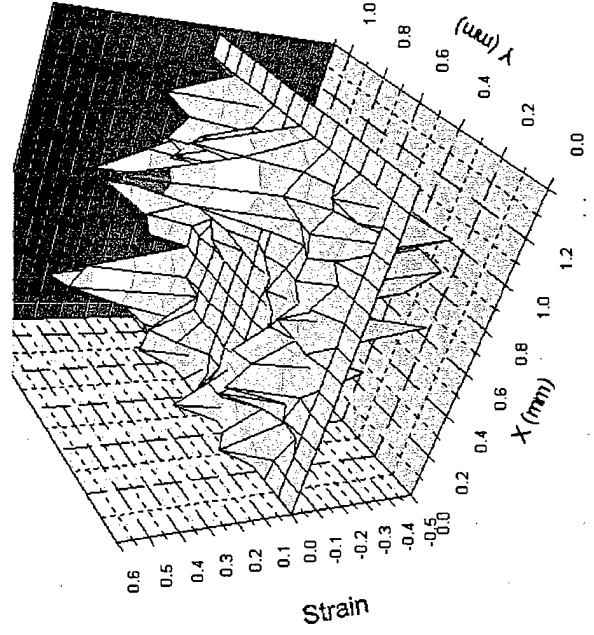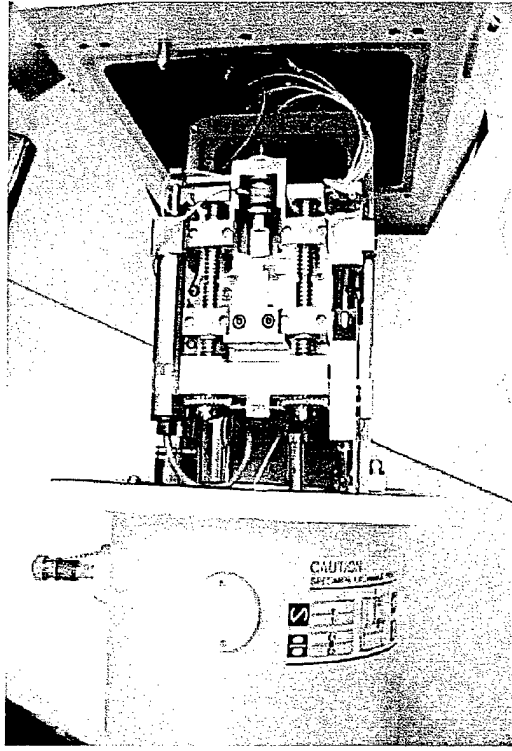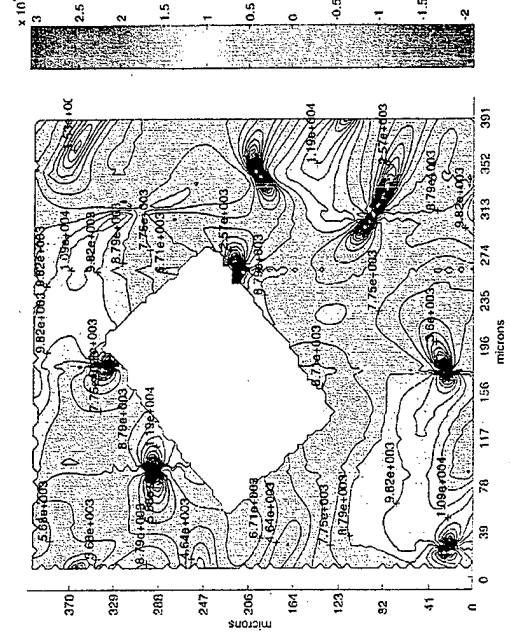
Under a Constant Load Condition and on the Meso-Scale, The Strain Distributions are highly Dependent on Time

- Micro-structure has a significant effect on the strain distribution in the highly filled particulate composite material.

- The failure location may change with time.
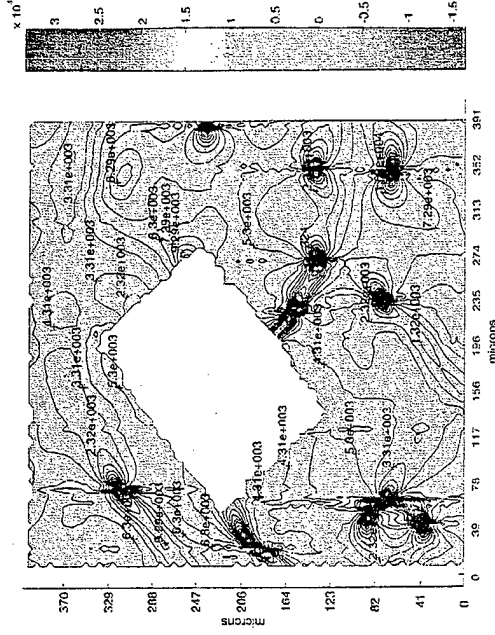
ε_y for 11.34 psi at 30 sec
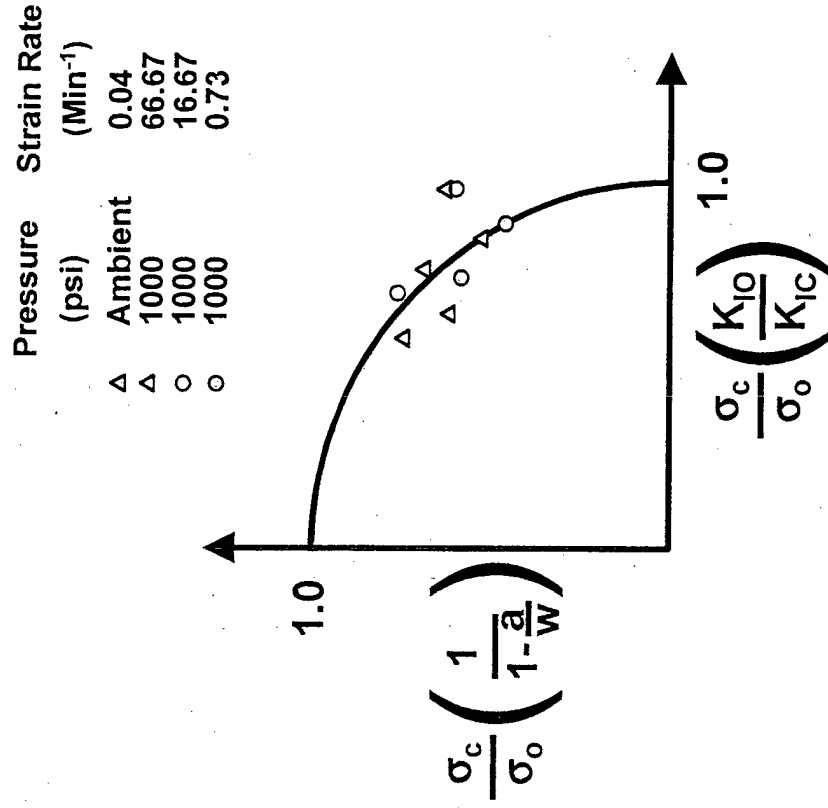
ε_y for 11.34 psi at 30 min

# A Good Correlation Exists between the Predicted and the Measured Critical Stresses for the Onset of Crack Growth

* A failure envelope was developed, based on strength of material and fracture mechanics theories, to predict the critical stress for the onset of crack growth.

$$\left(\frac{\sigma_c}{\sigma_o}\right)^2 \left(1-\frac{a}{w}\right)^{-2} + \left(\frac{\sigma_c}{\sigma_o}\right)^2 \left(\frac{K_{IO}}{K_{IC}}\right)^2 = 1$$

* The above equation holds for short and long cracks under different strain rate and confining pressure conditions.

Pressure (psi)	Strain Rate (Min^{-1})
$\triangle$ Ambient	0.04
$\triangle$ 1000	66.67
$\circ$ 1000	16.67
$\circ$ 1000	0.73

The Turning of the Off-Axis Crack Induces All Three Fracture Modes, Normal, In-Plane Shear, and Anti-Plane Shear.

* The river markings shown on the fracture surface indicate the existence of Mode III fracture along the crack front.

* The development of mixed-mode fracture during crack turning reduces the crack growth rate
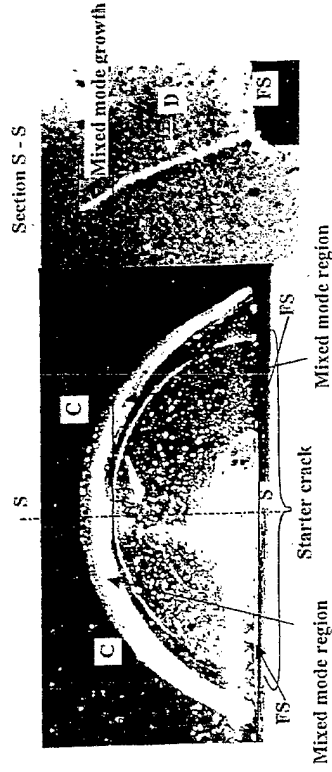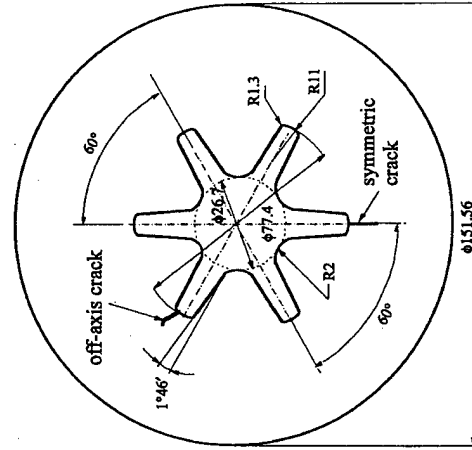
Model 4 Off-Axis Inclined Crack Showing Starter Crack and Final Crack Front
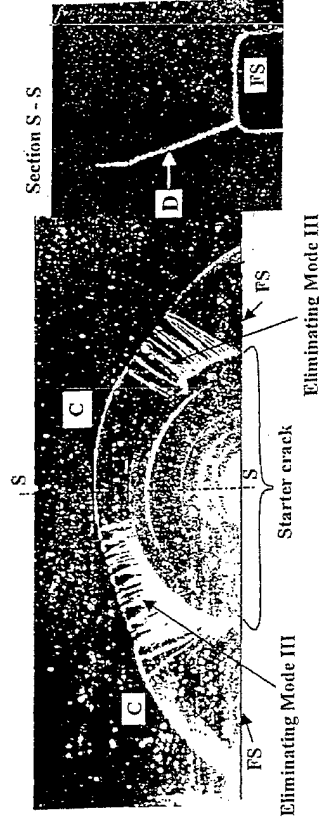
Model 8-i Off-Axis Inclined Crack Showing Starter Crack and Final Mode I Crack Front

magnification factor: 4.22

Conclusions

⊀ Under a constant strain rate loading condition, the failure mode changes when the confining pressure changes from ambient to 1000 psi.

⊀ A three-dimensional numerical simulation of particles interaction under multi-axial loading condition reveals that a high triaxial stress state developed near the particle surface.

⊀ Under a high confining pressure, microcracks can develop in the highly filled particulate composite material.

⊀ Under a constant load condition and on the meso-scale, the strain distributions are highly dependent on time.

⊀ The loading axiality has no significant effect on the critical damage intensity for the onset of crack growth.

⊀ The critical j-integral value for the onset of crack growth is insensitive to the loading history.

⊀ A good correlation exists between the predicted and the measured critical stresses for the onset of crack growth.